Assessment of the cycle-per-cycle noise level of the GEOSAT Follow-On, TOPEX, and POSEIDON altimeters

N. Tran, D. W. Hancock III, G. S. Hayne,

D. W. Lockwood, D. Vandemark, M. L. Driscoll[1], and R. V. Sailor[1]

NASA Goddard Space Flight Center/Wallops Flight Facility, Wallops Island, Virginia

[1] TASC Inc., Reading, Massachusetts

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corresponding author address: Dr. Ngan Tran, NASA GSFC/Wallops Flight Facility, Bldg. N-159 Rm E214, Wallops Island, VA 23337, e-mail: tran@osb1.wff.nasa.gov

Abstract

The GEOSAT Follow-on (GFO), TOPEX, and POSEIDON altimeter white noise levels have been evaluated using a new technique based on high-pass filtering of 1-Hz sea surface height time series. High-pass filtering removes the geoid and oceanography signals while revealing the random noise. The new filtering technique is simpler to use than the repeat-track method, gives essentially the same results, and makes it easier to analyze much larger amounts of data to investigate subtle variations in noise levels. The new noise level measurements provided here all show a stable noise process from cycle-to-cycle with a linear dependence of the noise level upon significant wave height (SWH). The GFO altimeter noise level is estimated to be about 2.5 cm for an SWH of 2 m. The POSEIDON noise level is estimated at 2.0 cm for the same value of 2 m SWH. The TOPEX altimeter noise level is about 1.8 cm when the dual-frequency ionospheric correction is included, but when this noisy correction is not used, the noise level is reduced to 1.5 cm at 2 m SWH. Although the dual-frequency ionospheric correction provides an average improvement over the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) correction, high-frequency noise enters into the dual-frequency correction from the Ku and C-band range noise. Since the variations in ionospheric refraction are a relatively long-wavelength global effect (with strong dependence on latitude), the dual-frequency ionospheric correction should be low-pass filtered before use, and this correction should not be included when estimating the high-frequency noise level of the altimeter.

1 Introduction

The GEOSAT Follow-on (GFO) and the TOPEX/POSEIDON (T/P) missions are dedicated to the observation of the ocean surface topography from orbit using satellite based nadir pointing radar altimeters. The basic data are altimeter-derived sea surface height (SSH) relative to the reference ellipsoid. The SSH is obtained by differencing the satellite altitude (relative to a reference ellipsoid) as determined by precision orbit tracking, and the altimeter range as determined by precise measurement of the round trip time of flight of the radar signal. The range estimate requires environmental corrections, e.g., for atmospheric propagation delays and sea-state biases. Measurements of the range in 1-s averages are generally analyzed in applications of altimeter data.

An integral part of the analysis of altimeter data sets is a quantitative evaluation of altimeter instrument noise. This is necessary for monitoring improvements in measurement systems, for projecting future capabilities, and for properly analyzing the data in oceanographic and geodetic applications. The precision of satellite radar altimeter instruments has improved since the earlier programs (GEOS-3, SEASAT, and GEOSAT), and continuous improvements in environmental corrections (orbits, ionospheric refraction, tides, etc.) has resulted in modern altimeters (e.g., TOPEX) having absolute errors of only a few centimeters.

The measured sea surface topography represents the sum of the heights of 1) geoid undulations, 2) dynamic oceanography associated with geostrophic surface currents and eddies, 3) tides, 4) the sea surface response to atmospheric pressure loading, and 5) altimeter instrument noise (not included in this list are orbit errors, which are very long wavelength, relatively small in amplitude, and may be ignored for the purpose of this discussion). The elevation variability of the geoid signal is on the order of meters to tens of meters; the oceanographic signals are from a few centimeters to no more than two meters; and tides in the open ocean are generally less than a meter but can be predicted by numerical models to better than a few centimeters. The atmospheric loading or "inverse barometer" effect is a few centimeters and the instrument noise is also at the few centimeter level. One additional, but small effect comes from ocean waves and swell. While very obvious to mariners, waves are not a major factor in the measured sea surface topography, because each altimeter pulse illuminates a circular area on the ocean that is several kilometers in diameter, so the local waves are approximately averaged out. Actually the averaging out is not perfect, and there is an "electromagnetic bias" correction proportional to significant wave height (SWH) and wind speed that should be made for the most precise uses of altimeter data [e.g., Gaspar et al., 1994].

The original analyses of satellite altimeter "noise" were developed in the context of geodesy, and "noise" was defined as any effect in the data other than the geoid signal. Noise was studied by comparing the repeatability of the data observed along collinear or repeat tracks. By differencing the data series along two repeat tracks (having a cross-track offset of no more than 1 km), the time-invariant geoid signal cancels out and a time series of random noise remains. Spectral analysis of the difference time series reveals two main components of the noise: 1) a "colored" noise process behaving approximately like a first-order Markov random process (this is attributable to oceanography); and 2) a lower-powered additive contribution that appears as a “white noise floor”, visible as the noise spectra flatten out at high frequency [Brammer and Sailor, 1980; LeSchack and Sailor, 1988]. The white noise component was attributed to electronic noise in the altimeter instrument, and indeed, the on-orbit results are generally consistent with laboratory measurements of instrument noise made before launch.

However, as this paper shows, a portion of the “white noise” component can be attributed to random scattering effects from ocean waves, since the white noise level is now found to be proportional to the SWH. The repeat-track method of studying noise in altimeter data requires that repeat tracks be matched up and aligned, that environmental corrections (e.g., tides) be applied independently to each track, and that power spectra be computed from the difference segments. This is straightforward but was not easily automated to process large amounts of data. Consequently, the early studies did not apply this method to very many repeat track pairs, and did not investigate in much detail the variability in noise that might occur as a function of aging of the spacecraft, or that might be due to environmental factors such as SWH. Nevertheless, the white noise level for each altimeter was found to be fairly consistent, and the average values obtained for different altimeters are a good measure of the relative quality of those instruments. For example, GEOS-3, launched in 1975, had a white noise level of about 23 cm. For SEASAT in 1978, the result is 5 cm, and for Geosat in 1985, 3 cm [Sailor and LeSchack, 1987; Sailor and Driscoll, 1992]. Le Traon et al. [1994] analyzed TOPEX and POSEIDON spectra and estimated that the POSEIDON repeat-track noise level is about 3 cm and the TOPEX repeat-track noise level is about 1.8 cm RMS. All of these numbers have been determined without consideration of the significant wave height (SWH). They all represent the integrated white noise power in the frequency band from -0.5 to + 0.5 Hz (the folding frequencies for data sampled at 1 Hz), so these noise values correspond to a 1-second average. Sailor [1993] defines the signal processing and spectral analysis techniques in detail, and gives examples that confirm the validity of the noise modeling approach involving repeat tracks.

More recently, investigations by Driscoll and Sailor [2001] have shown that, since white noise dominates the GFO altimeter sea surface height time series at the shortest wavelengths, a noise measurement algorithm that works by high-pass filtering 1-Hz data to estimate white noise level is a good and simple alternative method. They have demonstrated the robust nature of this simplified, single-track analysis approach that avoids the need to 1) obtain and align repeat-tracks, 2) apply environmental corrections, and 3) compute power spectra of difference time series. They used 52 GFO track segments for their study and the amount of data along these segments varied from approximately 180 to 830 samples. In addition to developing a single-track filtering method that gives the same results as the repeat-track method, they also showed that the noise level is sensitive to SWH; the noise level increases linearly with increasing SWH. The GFO altimeter was designed to have an RMS white noise level, based on 1-second height averages, of less than 3.5 cm for significant wave height less than 2 m. The results of Driscoll and Sailor's [2001] analysis show that the GFO noise level is better than 2.7 cm for SWH less than 2 m demonstrating that the GFO altimeter meets its design specification.

Several issues that have not been addressed in past analyses of radar altimeter performance will be discussed in the following. We will first extend this high-pass filterering method from a segment evaluation to a cycle evaluation for GFO data. This method is simple to implement as an automatic process and will serve the purpose of providing a cycle-by-cycle instrument characterization. We will then apply the method to quantify the white noise level of the TOPEX and POSEIDON altimeters data as a function of the significant wave height for comparison. In the TOPEX case, we compare the result with the operational dual-frequency range noise estimation. This latter technique has been developed specifically for a dual-frequency altimeter such as TOPEX, and is not applicable to a single-frequency altimeter such as GFO and POSEIDON. We will also discuss the influence of the atmospheric corrections to the range in the TOPEX noise level estimations.

Data sets and processing routine are described in the next section. Estimates of the GFO noise level are presented in the section 3. Sections 4 and 5 concern respectively TOPEX and POSEIDON altimeter noise analysis. The last section summarizes the main results of this study.

2 Data sets and routine

2.1 GEOSAT Follow-on

The GEOSAT Follow-on (GFO) program is a United States Navy project, one of a series of radar altimeter satellites. GFO was launched on 10 February 1998. Its primary instrument is a nadir pointing radar altimeter operating at a frequency of 13.5 GHz. Data presented here are based on the NGDR files, were collected from day 352 (17 December) of 2000 to day 155 (4 June) of 2001, and represent 10 repeat cycles of 17 days, cycle 1 through cycle 10. This study is based on the 1-Hz measurements of the SSH.

Rather stringent editing is applied to eliminate anomalous data. Data are discarded when they lie outside the latitude range 60^oS to 60^oN. In addition to the use of both GFO Quality Word I (bits: 0-9, 10, 11, 12, 13, 21, 22, 24, 27, 28, and 29) and Quality Word II (bits: 18, 19, and 20), all cases with radar cross-section (σ_0) and significant wave height (SWH) respectively above 16 dB and 10 m are also discarded.

2.2 TOPEX/POSEIDON

The TOPEX and POSEIDON altimeters fly on the T/P satellite launched August 10, 1992. This mission is jointly conducted by the US and the French space agencies. The altimeters are respectively designed by the National Aeronautics and Space Administration (NASA) and by the Centre National d'Etudes Spatiales (CNES). TOPEX is a dual-frequency Ku/C-band radar altimeter operating at 13.6 GHZ (Ku-band) and 5.3 GHz (C-band) simultaneously while POSEIDON is a single-frequency altimeter at 13.65 GHz. The TOPEX C-band capability is principally for improving estimates of the ionospheric correction. TOPEX is the primary sensor for the T/P mission, while POSEIDON is an experimental instrument used to validate the technology of a low-power, light-weight altimeter for future Earth-observing missions. It shares the antenna used by TOPEX; thus, only one altimeter operates at any given time. POSEIDON operates approximately 10% of the time.

The data sets are based on the Merged Geophysical Data Records (MGDR) files which are produced operationally, per cycle of 10 days, by the Archiving, Validation, and Interpretation of Satellite

Data in Oceanography (AVISO). These files contain data from both the TOPEX dual-frequency and the POSEIDON solid-state altimeter. For TOPEX the advantage is to have both main ionospheric corrections available. The TOPEX files, for this study, cover a period of 8 cycles, cycle 304 through cycle 312 except cycle 307, from day 349 (14 December) of 2000 to day 72 (13 March) of 2001. These cycles were chosen because they sampled the ocean surface during the same period of time as the first 5 cycles of GFO. The T/P files for the entire period covered by our chosen GFO cycles were not all available at the time of this study. Due to the relatively short period of time during which POSEIDON has been operating, our data set, over this period, contains only one cycle, cycle 307 from day 13 (13 January) to day 23 (23 January) of 2001. We added 5 more POSEIDON cycles acquired earlier, for assessment of the stability of the noise level estimation with time, cycles 243 and 266 in 1999 and cycles 278, 289 and 299 in 2000.

The measurements used are 1-second averages. The sea surface height measurements are obtained using either the NASA orbit or the CNES orbit depending on which altimeter is analyzed at the time. Note that since the two orbits agree to within a few centimeters [Morris and Gill, 1994], either of these orbits could have been used for both altimeters. The standard corrections applied to the range measurements to compute the sea surface height come from the same sources for both TOPEX and POSEIDON, except for the ionospheric correction. For TOPEX, the two-frequency measurements are used to compute the effect of ionospheric free electrons in the satellite range measurements. Since POSEIDON uses a single frequency, an external correction for the ionosphere must be applied. This latter comes from the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) measurements. Its main purpose is to constrain the computed position of the satellite, in conjunction with a large number of ground stations. DORIS also measures in two carrier frequencies (0.4 and 2 GHz) to correct for ionospheric delays to its signal, but the paths between the satellite and DORIS ground stations are usually slanted off the vertical, where the altimeter's path lies. These slant path delays are used together with an ionospheric model (Bent) to estimate the vertical path delay.

For this study, the altimeter data are also limited in space between latitudes 60^oS and 60^oN as applied for GFO data. In addition to the data flags, all cases with satellite attitude angle larger than 0.12^o are eliminated. Also discarded are measurements when the radar cross-section (σ_0) and the sea wave height are respectively above 16 dB and 10 m.

2.3 Data processing routine

The application of the editing procedure leads to gaps in the sea surface height time series. In order to not remove too many track segments, we filled the small gaps between 2 and 5 seconds by a linear interpolation. The high-pass filter is a 5th-order Butterworth filter (to remove the geoid and all long-wavelength environmental signal) with a cutoff frequency of 0.30 Hz as used by Driscoll and Sailor [2001]. It has been applied to GFO data on two different track segment sizes: 290-310 samples ($\sim$ 5 minutes) and 50-70 samples ($\sim$ 1 minute) respectively to evaluate the accuracy of the estimations. After filtering, the equivalent white noise level is computed by scaling the RMS value of the output time series. The scale factor for our particular Butterworth filter is 1.574 (scale factors for any given filter can be determined empirically by using white noise as an input and observing the RMS of the output). More details about the high-pass filter process itself can be found in Driscoll and Sailor's report [2001]. For both TOPEX and POSEIDON, only the 5-minute segments are considered in this paper. Smaller segments in each case are not considered.

3 GFO noise level

Figure 1 shows the spatial distribution of the 5-minute track segments used to assess the noise level for cycle 7 of GFO. The average number of segments per cycle is $\sim$1026 for the cycles used in this study. Note that, because of the editing process and the segment length choice, some regions of the global ocean such as the northern Indian Ocean, the Mediterranean sea or the western part of the North Atlantic Ocean are less represented than other regions, although most of the global ocean is covered. When the track segment length is reduced to a 1-minute interval, the average number of segments increases to $\sim$9400, and their spatial distribution provides better coverage of small areas (Figure not shown).

Figures 2 and 3 show the high-pass filtering estimates of the GFO RMS white noise level with respect to the SWH, based respectively on the 5-minute and 1-minute track segments of cycle 7 of

GFO. SWH averaged values along the track segments vary from 0.5 m to 7 m, providing a good sampling of calm to rough sea surface conditions. Values of RMS noise level are mostly between 2 and 6 cm for the 5-minute segments and between 1 and 7 cm for the 1-minute ones. In this latter plot, the data are shown by density contours in order to better display where most of the data are. The two-dimensional histogram exhibits a peak around 2 m SWH and 2.5 cm noise level. The decrease of the segment size from 5-minute to 1-minute increases the representation of thinner SWH intervals and extreme SWH values ($<$1.25 m and $>$5 m), leading to a larger variability of the noise level estimates with respect to SWH. The noise level is sensitive to SWH, with larger noise values associated with larger SWH. The straight line in Figures 2 and 3 represents the linear least-squares fit. As shown in Driscoll and Sailor's results [2001], the noise level increases linearly with increasing SWH.

Table 1 summarizes the averaged statistical indicators from such plots over the full set of 10 GFO cycles studied, while Figure 4 displays, as a function of the cycle number, the average value of the noise level and SWH for each cycle, along with the value of the noise level at 2 m SWH, determined from the linear fit. The small variations in the averaged noise level follow those in the averaged SWH. The noise level at 2 m SWH is a stable indicator that can be used to characterize the altimeter noise level for both track segment sizes. Table 1 shows a 6% decrease of the mean of the Ku SWH distribution when the segment size is reduced. The mean of the RMS noise level decreases from 3.08 to 2.98 cm, but the noise level at 2 m SWH increases from 2.51 to 2.58 cm. The slope of the linear fit between the RMS noise level and the Ku SWH shows a decrease of about 8.7%.

The results obtained with the 1-minute track segments do not differ much from the results obtained with the 5-minute segments. Since the results from the 5-minute segments exhibit a smaller variability in the noise level estimate with respect to SWH, we decided to use the high-pass filter approach with the 5-minute segment size on TOPEX and POSEIDON data, presented in the two next sections. The advantage of this noise estimation is that it can be applied to a single-frequency altimeter data as GFO or POSEIDON as well as to a dual-frequency altimeter data such as TOPEX. This method allows comparison of the quality of different altimeters in a straightforward manner without having to work with repeat-tracks.

4 TOPEX noise level

Figure 5 shows the high-pass filtering estimates of TOPEX RMS white noise level with respect to SWH for the 5-minute track segments of cycle 309 of TOPEX. The average number of segments per cycle is $\sim$510. Values of RMS noise level vary mostly between 1 and 3 cm, and this interval of variability is lower for TOPEX than for GFO (Figure 2). Table 2 presents the averaged statistical indicators computed over the 8 TOPEX cycles studied while Figure 6(a) displays the average value of the noise level and SWH for each cycle along with the value of the noise level at 2 m SWH as a function of the cycle number. The gap at cycle 307 is due to the operation of POSEIDON altimeter. The same comment as for GFO can be made; the noise level at 2 m SWH is a stable indicator, with an average value of $\sim$1.8 cm over the 8 TOPEX cycles. The mean value of the RMS noise level distribution for each cycle is a little bit higher with a value of $\sim$2.2 cm. Note that comparison of the slope of the linear fit between the noise level and SWH exhibits a lower value for TOPEX than for GFO.

4.1 Dual-frequency ionosphere correction effect

In the TOPEX case, there are additional considerations when quantifying our results. The high-pass filter is applied to the sea surface height values which are computed from the satellite altitude and the altimeter range with atmospheric propagation corrections. We note that estimating the white noise level based on the sea surface height measurements could be viewed as an estimation of the white noise level on the altimeter range itself if there were no high frequency content in the atmospheric corrections. But as recalled by Stammer and Wunsch [1994], Callahan [1992] recognized that this correction could be noisy and recommended that the raw ionospheric corrections should be averaged over a 21-s moving window to eliminate high-frequency noise. This noise comes from the TOPEX algorithm used to compute the ionospheric correction. The ionosphere directly impacts the altimeter measurement by increasing the electromagnetic path delay to the surface in proportion to the total electron content along the path; that increase would translate as errors in sea level. Since the delay is inversely proportional to frequency squared, the TOPEX dual-frequency altimeter uses the dispersion of the ionosphere to measure this delay at two different frequencies, allowing the error to be corrected.

By employing range measurements at a different frequency from a second altimeter to obtain an ionosphere correction, one propagates the errors from both individual ranges into this correction. Thus the ionosphere correction, contaminated with the altimeter range measurement noise, has high-frequency components that raise the noise level estimated by high-pass filtering the 1-Hz TOPEX SSH data.

Table 2 also presents the averaged statistical indicators estimated from the SSH measurements time series after removing the ionospheric corrections. Figure 6(b) shows the revised variations with respect to the cycle number, clearly indicating a decrease of the noise level. The mean value of the RMS noise level distribution for each cycle is reduced to about 1.8-2.0 cm which represents a decrease of 13.3%. The noise level at 2 m SWH decreases by 14.6% and becomes $\sim$1.5 cm. The slope of the linear fit decreased by 7.3%, which is explained by the fact that both the range noise, which is correlated with SWH, and the ionospheric electron content exhibit a latitudinal dependence.

The total electron content of the ionosphere varies depending upon the time of day, solar conditions, geographic location, and satellite altitude [Callahan, 1984]. Total electron content is largest when the Sun is overhead and at all local times along the geomagnetic equator. But these variations are generally long wavelength. The ionosphere correction is then on average correlated with ocean SWH through its latitudinal dependence [Imel, 1994]. The ionospheric electron content and SWH show a 15% correlation [Zlotnicki, 1994]. So the relationship between the noise level estimates and SWH changes when we remove the ionosphere correction, leading to the observed change in the slope of the linear fit.

We next used the DORIS ionosphere correction provided by CNES as an independent source to verify that the high-frequency component in the dual-frequency ionospheric correction comes from the range measurement noise. The advantage of the DORIS ionosphere correction over the NASA one is that it is independent of the altimeter range measurement. Its disadvantage is that in general it is slightly less accurate because the ionosphere sampled by the DORIS system is not the ionosphere sampled by the altimeter. Ionospheric electron content from DORIS, which involves a space-time interpolation among slant paths between the satellite and fixed ground stations, should have larger errors near the equator, where the large electron content variability may not be sampled rapidly enough or closely enough [Zlotnicki, 1994]. Evaluation of the ionospheric correction by Morris and Gill [1994] indicates that the dual-frequency correction provides an accuracy gain over the DORIS correction. Le Traon et al. [1994] also conclude that the dual-frequency ionospheric correction performs slightly better than the DORIS ionospheric corrections. There is an average bias of about 1 cm between the dual-frequency ionosphere estimates and the DORIS model [Imel, 1994].

The replacement of the dual-frequency ionosphere correction by the DORIS one leads to the result that the RMS noise level stays low as it was when we simply removed the TOPEX ionosphere correction from the sea surface height before applying the high-pass filtering process. Thus the TOPEX dual-frequency ionospheric correction clearly introduces additional high-frequency noise leading to an increase of the RMS noise level estimated by high-pass filtering the sea surface height time series. So for the purpose of characterizing the noise level related to the altimeter instrument, it is better to first low-pass filter, or just not use, any corrections that are not long-wavelength in nature.

The two other atmospheric corrections, the dry and wet tropospheric corrections, are both long wavelength effects that do not contain high-frequency noise. The dry tropospheric correction is determined from the European Center for Medium-Range Weather Forecasts (ECMWF) model surface pressure values, and the wet tropospheric correction comes from the TOPEX microwave radiometer. We verified that removing both from the SSH measurements does not change the noise level estimates. Note that for GFO data, the ionospheric correction comes from ionosphere models and should not impact the noise level estimation.

4.2 Comparison with Wallops operational estimation

The technique we have been using to this point at Wallops to estimate the performance of the TOPEX altimeter is based on calculating the RMS of one-per-frame Ku-minus-C height differences, after a linear fit over a 1-minute interval. The height RMS for the Ku-band is then determined by scaling the rms-of-fit by the ratio of the Ku/C noise. In most of the TOPEX data, the C-band range standard deviation is expected to be between one to two times the Ku-band range standard deviation (because of a poorer signal-to-noise ratio and less pulse-to-pulse averaging); a fixed ratio of 1.6 has been used. This method takes the effects of geoid variation out of the calculation that would be present on a straight fit to either frequency, since both frequencies follow the same geoid tracking. This method has been developed specifically for a dual-frequency altimeter such as TOPEX and cannot be used for a single-frequency altimeter.

In order to compare with the Wallops operational estimation of the 1-minute averaged Ku-band range noise, we compute the noise level estimates on the 1-minute track segments of the “uncorrected” SSH time series, i.e. computed with the “uncorrected” range (without the ionospheric correction and the sea-state bias). Indeed, the sea-state bias, similar to the dual-frequency ionospheric correction, has a high-frequency component. This is due to the same reason; both the dual-frequency ionosphere correction and the sea state bias are obtained using empirical models derived from analyses of altimeter data itself. The sea state bias is computed from SWH and from the wind speed derived from the radar cross section [Gaspar et al., 1994]. In Results by using the combined dual-frequency range along with the Ku- and C-band ranges are presented in Table 3. As expected, the C-band noise (average value of 3.36 cm) is higher than the Ku-band noise (average value of 1.76 cm) and the combined noise (average value of 1.91 cm) lies between the two while it is closer to the Ku-band noise. The combined range is computed as, $R = 1.18R_{Ku} - 0.18R_C$ [Chelton et al., 2001]. It is apparent that the combined range weights the Ku-band range estimate about 6.6 times greater than the C-band range. The higher C-band measurement errors are of secondary concern in the combined range noise since they are reduced by the multiplicative factor 0.18. Table 4 summarizes TOPEX altimeter performance, listing the RMS noise level of the combined-frequency, Ku-band, and C-band altimeter at respectively 2, 4, and 6 m SWH. The ratio between C- and Ku-band varies between 1.7 and 2.0 with respect to SWH.

The Wallops Ku-band range noise estimation also displays a linear trend with respect to SWH (Figure not shown). The averaged statistical indicators computed from this method are included in Table 3. All results in this Table are derived from $\sim$ 5400 RMS noise estimates. The mean value of the Wallops Ku-band range noise level and the value at 2 m SWH from the linear fit with respect to the cycle number are shown in Figure 6(c). Both variations are stable with time. The noise level computed directly from the 1-minute Ku-band range exhibits higher values by 4% for the mean and by 10% for the noise level at 2 m SWH than the ones obtained using the high-pass filtering method applied on 1-minute track segments and using Ku-band range. This is related to the fact that the operational algorithm used a fixed value for the ratio between the C-band and the Ku-band noise whereas this ratio changes with SWH (as seen in Table 4). Although the two linear fits are quite different, the mean value of both distributions and the noise level estimates at 2 m SWH are sufficiently close to conclude with confidence that these methods are equivalent.

5 POSEIDON noise level

Figure 7 shows the high-pass filtering estimates of the POSEIDON RMS white noise level with respect to SWH based for the 5-minute track segments of cycle 307 of POSEIDON. Table 5 presents the averaged statistical indicators computed over the six POSEIDON cycles studied. Figure 8 displays the average value of the noise level and SWH for each cycle along with the value of the noise level at 2 m SWH as a function of the cycle number. There are about 600 5-minute track segments for each cycle. Note the very stable value of the RMS noise level at 2 m SWH over time. It is $\sim$2.0 cm and the averaged value for a cycle is $\sim$ 2.5 cm. This latter is slightly lower than the estimate reported by Le Traon et al. [1994] who found that the POSEIDON repeat-track noise level is about 3 cm.

The high-pass filtering process will be applied to the upcoming data of Jason-1, the follow-on to the highly successful TOPEX/POSEIDON mission; Jason-1 will be launched at the end of 2001 and carries the CNES POSEIDON-2 altimeter (C- and Ku-band).

6 Summary and conclusion

The assessment of the altimeter noise by high-pass filtering 1-Hz sea surface height time series can be applied to single-frequency altimeter data such as GFO and the French altimeter POSEIDON as well as dual-frequency altimeter data such as TOPEX. This new approach to estimate the altimeter noise provides results similar to those derived from the noise spectra computed from differenced repeating ground tracks [Driscoll and Sailor, 2001] and is also in agreement with the Wallops TOPEX Ku-band range noise estimation method.

Our analysis quantifies the performance of GFO, TOPEX, and POSEIDON altimeters by evaluating the RMS white noise level as a function of SWH. Table 6 summarizes the Ku-band altimeter performance for GFO, TOPEX, and POSEIDON based on the 5-minute segments of SSH time series, listing the RMS noise level of each altimeter at respectively 2, 4, and 6 m SWH. The RMS noise level of TOPEX based on SSH measurements without the ionospheric correction is the lowest at each SWH with a value of $\sim$1.5 cm at 2 m SWH. POSEIDON altimeter noise is higher with a value of $\sim$2.0 cm and GFO altimeter noise is the highest with 2.5 cm for the same SWH of 2 m.

This paper presents the first large-scale application of the high-pass filtering method for determining the noise level in satellite altimeter data. This new technique is valuable because it allows the noise levels to be determined from individual tracks, rather than from repeat tracks, so it is easy to observe how the noise level varies with time. The most obvious effect on the observed noise level is SWH, and for all altimeters, the noise level increases linearly with increasing SWH. Other than the dependence on SWH, the noise level is very stable from cycle to cycle for GFO, TOPEX, and POSEIDON. Thus, the high-pass filtering technique will be useful for monitoring the performance of any altimeter as the satellite ages, and for comparing the relative performance of different altimeters with respect to high-frequency noise.

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Table 1: Statistical indicators for GFO based on 5-minute and 1-minute track segments. The values represent averages over the 10 cycles analyzed.

GFO	Ku SWH Mean (m)	Ku SWH Std Dev (m)	Noise Level (NL) Mean (cm)	Noise Level (NL) Std Dev (cm)	Noise Level vs. Ku SWH Slope	Intercept	NL at 2m SWH
5-minute	2.745	1.085	3.077	0.883	0.754 ± 0.010	1.006	2.515
1-minute	2.580	1.225	2.978	1.154	0.688 ± 0.006	1.202	2.579

Table 2: Statistical indicators for TOPEX based on 5-minute segments. The values represent averages over the 8 cycles analyzed. (w/o: without)

TOPEX	Ku SWH Mean (m)	Ku SWH Std Dev (m)	Noise Level (NL) Mean (cm)	Noise Level (NL) Std Dev (cm)	Noise Level vs. Ku SWH Slope	Intercept	NL at 2m SWH
with Iono	2.831	1.015	2.177	0.524	0.466 ± 0.010	0.855	1.788
w/o Iono	2.831	1.015	1.888	0.487	0.432 ± 0.010	0.662	1.527

Table 3: Statistical indicators for TOPEX based on 1-minute track segments. The values represent averages over the 8 cycles analyzed.

TOPEX	Ku SWH Mean (m)	Ku SWH Std Dev (m)	Noise Level (NL) Mean (cm)	Noise Level (NL) Std Dev (cm)	Noise Level vs. Ku SWH Slope	Intercept	NL at 2m SWH
combined	2.793	1.216	1.913	0.704	0.417 ± 0.006	0.749	1.582
Ku-band	2.793	1.216	1.764	0.675	0.397 ± 0.005	0.653	1.448
C-band	2.793	1.216	3.357	0.988	0.558 ± 0.008	1.800	2.916
dual-freq.	2.824	1.139	1.838	0.421	0.292 ± 0.006	1.014	1.597

Table 4: Altimeter performance for TOPEX combined-frequency, Ku-band, and C-band at 2, 4, and 6 m SWH, based on the 1-minute segments of SSH time series computed with the uncorrected range values.

Altimeter 1-minute	Ku SWH (m) 2	4	6
combined	1.58	2.41	3.25
Ku-band	1.45	2.24	3.04
C-band	2.92	4.03	5.15

Table 5: Statistical indicators for POSEIDON based on 5-minute track segments. The values represent averages over the 6 cycles analyzed.

POSEIDON	Ku SWH		Noise Level (NL)		Noise Level vs. Ku SWH		
	Mean (m)	Std Dev (m)	Mean (cm)	Std Dev (cm)	Slope	Intercept	NL at 2m SWH
5-minute	2.977	1.139	2.543	0.695	0.519 ± 0.013	1.000	2.036

Table 6: Altimeter performance for GFO, TOPEX, and POSEIDON at 2, 4, and 6 m SWH, based on the 5-minute segments of SSH time series, except for TOPEX for which we removed the ionospheric correction in the SSH measurements.

Altimeter	Ku SWH (m)		
5-minute	2	4	6
GFO	2.51	4.02	5.53
TOPEX (w/o Iono)	1.53	2.39	3.25
POSEIDON	2.04	3.07	4.11

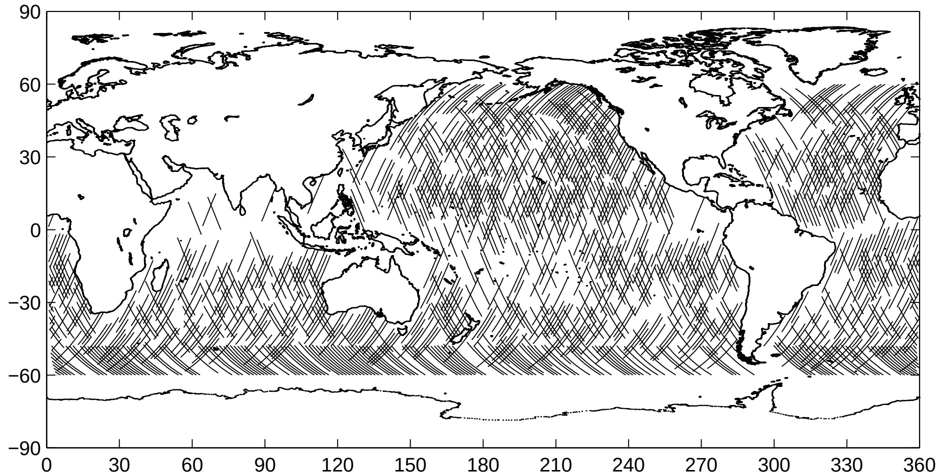

Figure 1: Spatial distribution of the 5-minute track segments used to assess the noise level estimates for cycle 7 of GFO.

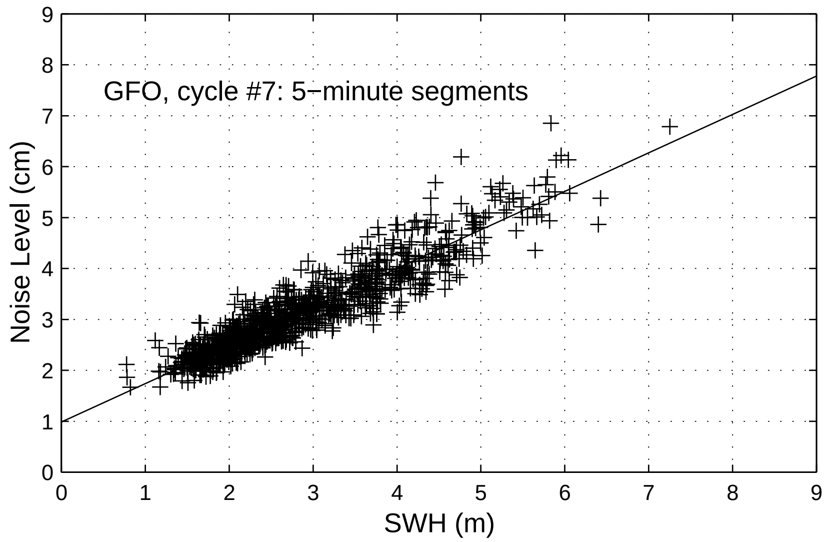

Figure 2: GFO RMS white noise level estimates with respect to significant wave height based on 5-minute track segments of cycle 7 of GFO.

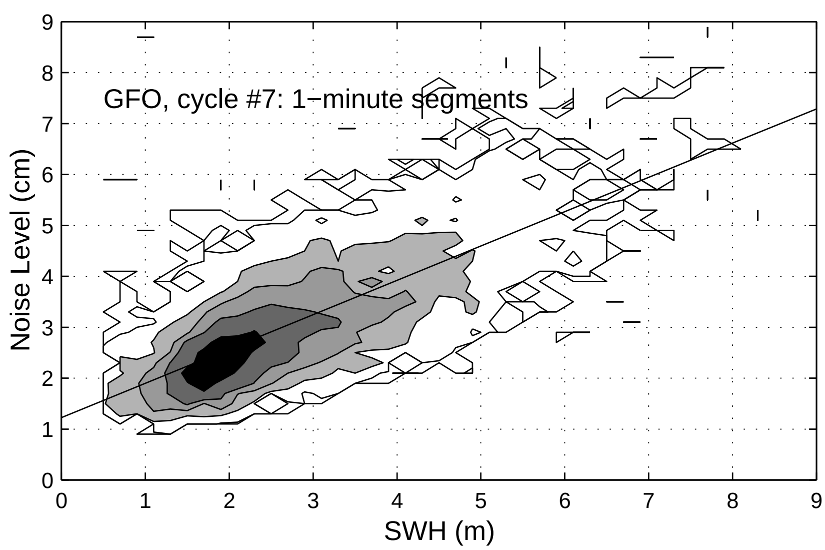

Figure 3: GFO RMS white noise level estimates with respect to significant wave height based on 1-minute track segments of cycle 7.

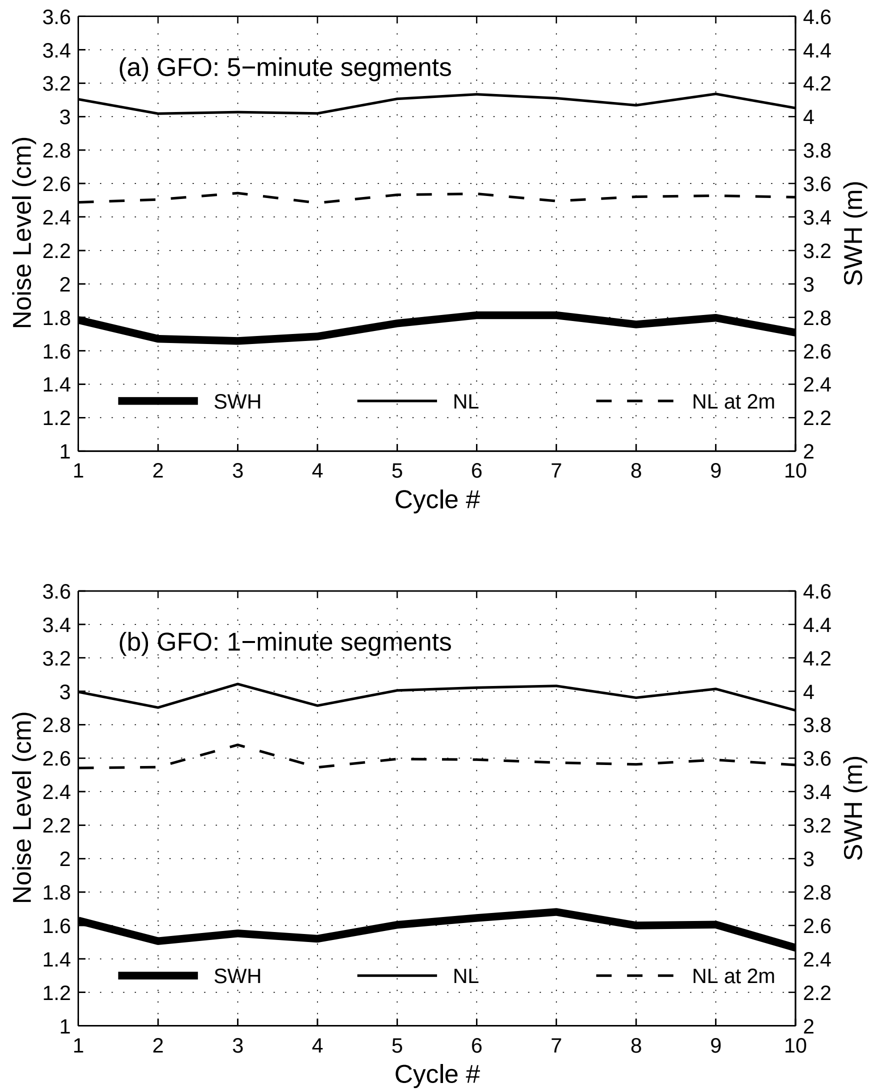

Figure 4: Variation of the average value of the noise level and SWH for each GFO cycle along with the value of the noise level at 2 m SWH, determined from the linear fit, as a function of the cycle number. The top panel is for 5-minute segments, and the bottom panel represents the results for the 1-minute segments.

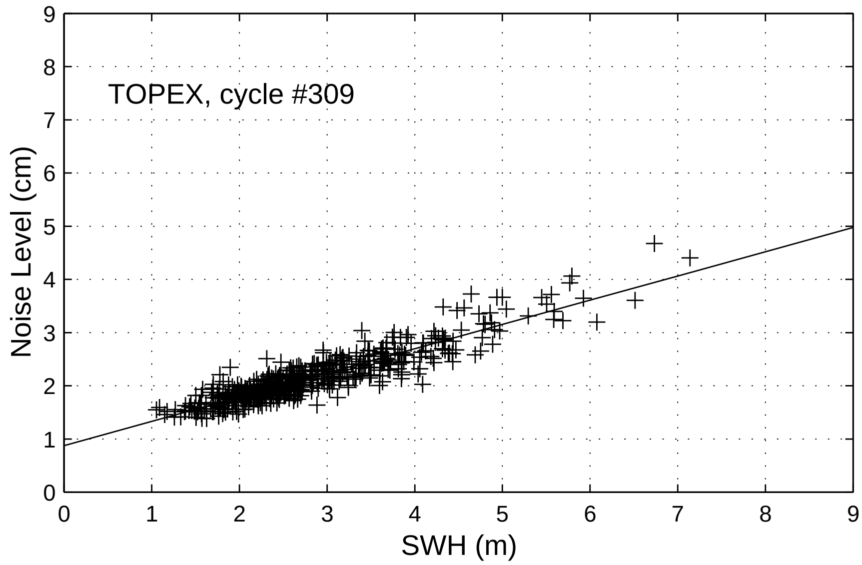

Figure 5: TOPEX RMS white noise level estimates with respect to significant wave height based on 5-minute track segments of cycle 309.

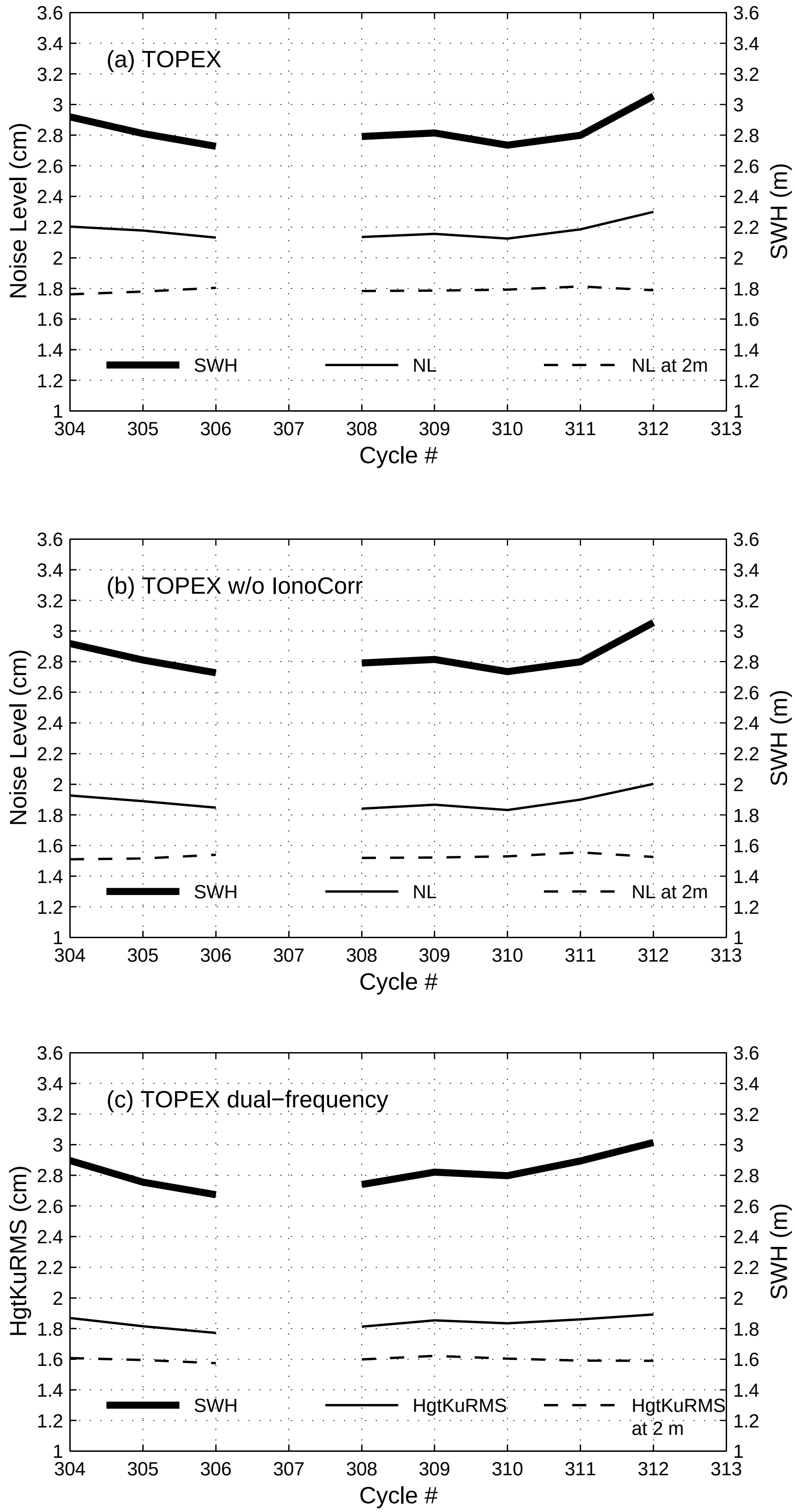

Figure 6: Variation of the average value of the noise level (5-minute segments) and SWH for each TOPEX cycle along with the value of the noise level at 2 m SWH, determined from the linear fit, as a function of the cycle number. Panel (a) is computed from SSH, panel (b) is computed from SSH after removing the TOPEX ionospheric correction, and panel (c) is computed by the dual-frequency method.

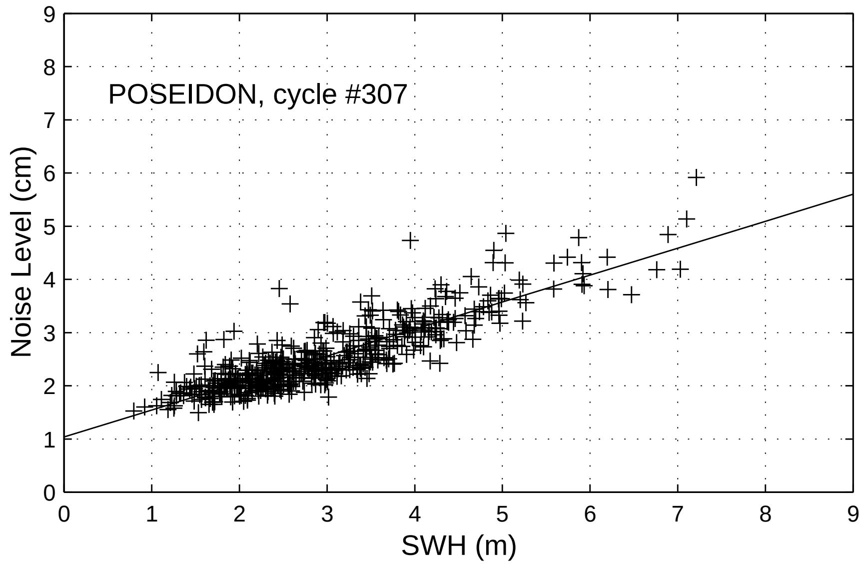

Figure 7: POSEIDON RMS white noise level estimates with respect to significant wave height based on 5-minute track segments of cycle 307.

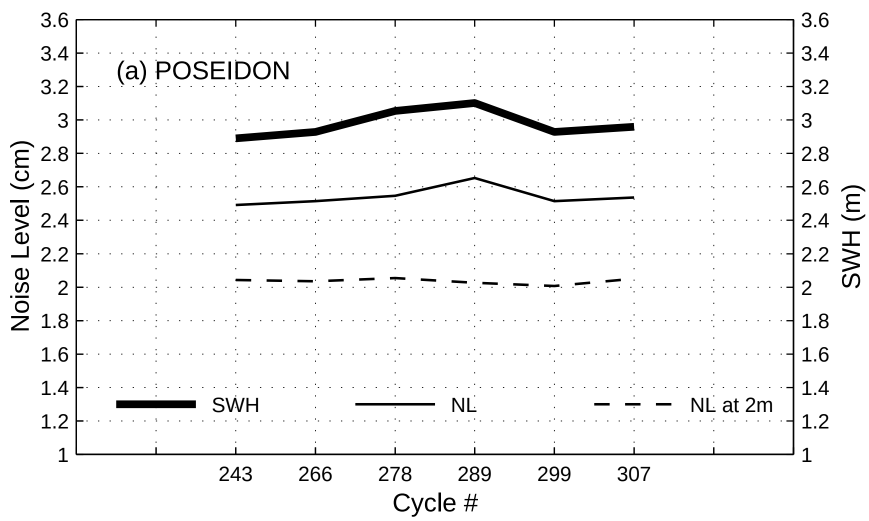

Figure 8: Variation of the average value of the noise level (5-minute segments) and SWH for each POSEIDON cycle (note the time discontinuities) along with the value of the noise level at 2 m SWH, determined from the linear fit, as a function of the cycle number.